

8

TRANSPORT PHENOMENA

R. BYRON BIRD
WARREN E. STEWART
EDWIN N. LIGHTFOOT

Department of Chemical Engineering
University of Wisconsin
Madison, Wisconsin

John Wiley & Sons, Inc.
New York • London • Sydney

COPYRIGHT © 1960 BY JOHN WILEY & SONS, INC.

All rights reserved. This book or any part thereof must not be reproduced in any form without the written permission of the publisher.

20

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 60-11717
PRINTED IN THE UNITED STATES OF AMERICA
ISBN 0 471 07392 X

Preface

This book is intended to present the subjects of molecular transport (heat conduction, convection, and diffusion). In this treatment, the molecular and continuum approaches are compared, although it should be emphasized that the book is not intended for complete mastery of the subjects.

Because of the current emphasis on understanding the use of empiricism, we feel that this book is of the kind. Obviously the subject is treated across traditional departmental boundaries. The subject of transport phenomena is treated in terms of mechanics, and electromagnetism. Knowledge of the subject of transport has certainly become an important part of engineering analysis. In addition, the book is of interest to some who are working in meteorology, and biology.

Acknowledgments

the manuscript
racy of the final
d O. Edwards,
Sánchez Palma,
ard, Boudewijn
lition the follow-
o all of the Class
owski, Richard

ie University of
leasant associa-
it to the subject
ate course; our

Holland) in 1956
brtverschijnselen,
teach transport
ad the pleasure
as a Fulbright
ie profited very
ort phenomena.
for typing the
We are deeply
orts in mimeo-
re wish to thank
e preparation of

R. B. B.
W. E. S.
E. N. L.

Contents

PART I MOMENTUM TRANSPORT

Chapter 1	Viscosity and the Mechanism of Momentum Transport	3
*§1.1	Newton's Law of Viscosity	3
	*Example 1.1-1. Calculation of Momentum Flux, 7	
*§1.2	Non-Newtonian Fluids	10
*§1.3	Pressure and Temperature Dependence of Viscosity	15
	*Example 1.3-1. Estimation of Viscosity from Critical Properties, 18	
	*Example 1.3-2. Effect of Pressure on Gas Viscosity, 19	
§1.4	Theory of Viscosity of Gases at Low Density	19
	Example 1.4-1. Computation of the Viscosity of a Gas at Low Density, 25	
	Example 1.4-2. Prediction of the Viscosity of a Gas Mixture at Low Density, 25	
§1.5	Theory of Viscosity of Liquids	26
	Example 1.5-1. Estimation of the Viscosity of a Pure Liquid, 29	
Chapter 2	Velocity Distributions in Laminar Flow	34
*§2.1	Shell Momentum Balances: Boundary Conditions	35
*§2.2	Flow of a Falling Film	37
	*Example 2.2-1. Calculation of Film Velocity, 41	
	Example 2.2-2. Falling Film with Variable Viscosity, 41	

xi

*§2.3	Flow through a Circular Tube	42
	*Example 2.3-1. Determination of Viscosity from Capillary Flow Data, 48	
	Example 2.3-2. Bingham Flow in a Circular Tube, 48	
*§2.4	Flow through an Annulus	51
§2.5	Adjacent Flow of Two Immiscible Fluids	54
*§2.6	Creeping Flow Around a Solid Sphere	56
	*Example 2.6-1. Determination of Viscosity from Terminal Velocity of a Falling Sphere, 60	

Chapter 3 The Equations of Change for Isothermal Systems

*§3.1	The Equation of Continuity	71
*§3.2	The Equation of Motion	74
§3.3	The Equation of Mechanical Energy	76
*§3.4	The Equations of Change in Curvilinear Coordinates	81
*§3.5	Use of the Equations of Change to Set Up Steady Flow Problems	82
	*Example 3.5-1. Tangential Annular Flow of a Newtonian Fluid, 94	92
	*Example 3.5-2. Shape of the Surface of a Rotating Liquid, 96	
	Example 3.5-3. Torque Relationships and Velocity Distribution in the Cone-and-Plate Viscometer, 98	
§3.6	The Equations of Change for Incompressible Non-Newtonian Flow	101
	Example 3.6-1. Tangential Annular Flow of a Bingham Plastic, 104	
	Example 3.6-2. Components of the Momentum Flux Tensor for Non-Newtonian Radial Flow between Two Parallel Disks, 106	

*§3.7	Dimensional Analysis of the Equations of Change	107
-------	---	-----

 *Example 3.7-1. Prediction of Vortex Depth in an Agitated Tank, 108

Chapter 4 Velocity Distributions with More Than One Independent Variable

*§4.1	Unsteady Viscous Flow	123
	*Example 4.1-1. Flow Near a Wall Suddenly Set in Motion, 124	
	Example 4.1-2. Unsteady Laminar Flow in a Circular Tube, 126	
§4.2	Steady Viscous Flow With Two Nonvanishing Velocity Components: The Stream Function	130
	Example 4.2-1. "Creeping Flow" Around a Sphere, 132	

§4.3	Steady Two-Dimensional Potential Flow	133
	Example 4.3-1. Ideal Flow Around a Cylinder, 136	
	Example 4.3-2. Flow into a Rectangular Channel, 138	
§4.4	Boundary-Layer Theory	140
	Example 4.4-1. Flow Near a Wall Suddenly Set in Motion, 140	
	Example 4.4-2. Flow Near the Leading Edge of a Flat Plate, 142	

Chapter 5 Velocity Distributions in Turbulent Flow

*§5.1	Fluctuations and Time-Smoothed Quantities	153
*§5.2	Time-Smoothing of the Equations of Change for an Incompressible Fluid	154
*§5.3	Semiempirical Expressions for the Reynolds Stresses	158
	*Example 5.3-1. Derivation of the Logarithmic Distribution Law for Tube Flow (Far from Wall), 161	
	*Example 5.3-2. Velocity Distribution for Tube Flow (Near Wall), 163	
	*Example 5.3-3. Relative Magnitude of Molecular and Eddy Viscosity, 165	
§5.4	The Second-Order Correlation Tensor and Its Propagation (the von Kármán-Howarth Equation)	166
	Example 5.4-1. Decay of Turbulence Behind a Grid, 173	

Chapter 6 Interphase Transport in Isothermal Systems

*§6.1	Definition of Friction Factors	180
*§6.2	Friction Factors for Flow in Tubes	181
	*Example 6.2-1. Pressure Drop Required for a Given Flow Rate, 188	183
	*Example 6.2-2. Flow Rate for a Given Pressure Drop, 189	
*§6.3	Friction Factors for Flow Around Spheres	190
	*Example 6.3-1. Determination of Diameter of a Falling Sphere, 194	
§6.4	Friction Factors for Packed Columns	196

Chapter 7 Macroscopic Balances for Isothermal Systems

*§7.1	The Macroscopic Mass Balance	208
*§7.2	The Macroscopic Momentum Balance	209
*§7.3	The Macroscopic Mechanical Energy Balances (Bernoulli equation)	210
	Example 7.3-1. Derivation of Mechanical Energy Balance for Steady Incompressible Flow, 213	
*§7.4	Estimation of the Friction Loss	214
	*Formula 7.4-1. Power Requirements for Pipe-Line Flow, 217	

*§7.5	Use of the Macroscopic Balances to Set Up Steady Flow Problems	219
	*Example 7.5-1. <i>Pressure Rise and Friction Loss in a Sudden Expansion</i> , 219	
	*Example 7.5-2. <i>Performance of a Liquid-Liquid Ejector</i> , 220	
	*Example 7.5-3. <i>Thrust on a Pipe Bend</i> , 222	
	*Example 7.5-4. <i>Isothermal Flow of a Liquid through an Orifice</i> , 224	
§7.6	Use of the Macroscopic Balances to Set Up Unsteady Flow Problems	226
	Example 7.6-1. <i>Efflux Time for Flow from a Funnel</i> , 226	
	Example 7.6-2. <i>Oscillation of a Damped Manometer</i> , 229	

PART II ENERGY TRANSPORT

Chapter 8 Thermal Conductivity and the Mechanism of Energy Transport 243

*§8.1	Fourier's Law of Heat Conduction	244
	*Example 8.1-1. <i>Measurement of Thermal Conductivity</i> , 247	
*§8.2	Temperature and Pressure Dependence of Thermal Conductivity in Gases and Liquids	249
	*Example 8.2-1. <i>Effect of Pressure on Thermal Conductivity</i> , 251	
§8.3	Theory of Thermal Conductivity of Gases at Low Density	253
	Example 8.3-1. <i>Computation of the Thermal Conductivity of a Monatomic Gas at Low Density</i> , 258	
	Example 8.3-2. <i>Estimation of the Thermal Conductivity of a Polyatomic Gas at Low Density</i> , 258	
	Example 8.3-3. <i>Prediction of the Thermal Conductivity of a Gas Mixture at Low Density</i> , 259	
§8.4	Theory of Thermal Conductivity of Liquids	260
	Example 8.4-1. <i>Prediction of the Thermal Conductivity of a Liquid</i> , 261	
§8.5	Thermal Conductivity of Solids	262

Chapter 9 Temperature Distributions in Solids and in Laminar Flow 265

*§9.1	Shell Energy Balances; Boundary Conditions	266
*§9.2	Heat Conduction with an Electrical Heat Source	267
	*Example 9.2-1. <i>Voltage Required for a Given Temperature Rise in a Wire Heated by an Electric Current</i> , 271	
	Example 9.2-2. <i>Heating of an Electric Wire with Temperature-Dependent Electrical and Thermal Conductivity</i> , 272	

§9.3	Heat Conduction with a Nuclear Heat Source	274
*§9.4	Heat Conduction with a Viscous Heat Source	276
§9.5	Heat Conduction with a Chemical Heat Source	279
*§9.6	Heat Conduction through Composite Walls: Addition of Resistances	283
	*Example 9.6-1. <i>Composite Cylindrical Walls</i> , 286	
§9.7	Heat Conduction in a Cooling Fin	288
	Example 9.7-1. <i>Error in Thermocouple Measurement</i> , 290	
*§9.8	Forced Convection	291
*§9.9	Free Convection	297

Chapter 10 The Equations of Change for Nonisothermal Systems 310

*§10.1	The Equations of Energy	311
*§10.2	The Energy Equation in Curvilinear Coordinates	317
*§10.3	The Equations of Motion for Forced and Free Convection in Nonisothermal Flow	317
*§10.4	Summary of the Equations of Change	321
*§10.5	Use of the Equations of Change to Set Up Steady-State Heat Transfer Problems	321
	*Example 10.5-1. <i>Tangential Flow in an Annulus with Viscous Heat Generation</i> , 325	
	*Example 10.5-2. <i>Steady Flow of a Nonisothermal Film</i> , 326	
	*Example 10.5-3. <i>Transpiration Cooling</i> , 328	
	Example 10.5-4. <i>Free-Convection Heat Transfer from a Vertical Plate</i> , 330	
	Example 10.5-5. <i>One-Dimensional Compressible Flow: Velocity, Temperature, and Pressure Gradients in a Stationary Shock Wave</i> , 333	
	*Example 10.5-6. <i>Adiabatic Frictionless Processes in an Ideal Gas</i> , 337	
*§10.6	Dimensional Analysis of the Equations of Change	338
	*Example 10.6-1. <i>Forced-Convection Heat Transfer in an Agitated Tank</i> , 339	
	*Example 10.6-2. <i>Surface Temperature of an Electric Heating Coil</i> , 340	

Chapter 11 Temperature Distributions with More Than One Independent Variable 352

*§11.1	Unsteady Heat Conduction in Solids	352
	*Example 11.1-1. <i>Heating of a Semi-Infinite Slab</i> , 353	
	*Example 11.1-2. <i>Heating of a Finite Slab</i> , 354	
	Example 11.1-3. <i>Cooling of a Sphere in Contact with a Well-Stirred Fluid</i> , 357	

§11.2	Steady Heat Conduction in Laminar Flow of a Viscous Fluid	361
	<i>Example 11.2-1: Laminar Tube Flow with Constant Heat Flux at Wall, 362</i>	
	<i>Example 11.2-2: Laminar Tube Flow with Constant Heat Flux at Wall: Asymptotic Solution for Small Distances, 363</i>	
§11.3	Steady Two-Dimensional Potential Flow of Heat in Solids	364
	<i>Example 11.3-1. Temperature Distribution in a Wall, 365</i>	
§11.4	Boundary-Layer Theory	366
	<i>Example 11.4-1. Heat Transfer in Forced-Convection Laminar Flow along a Heated Flat Plate, 367</i>	
Chapter 12	Temperature Distributions in Turbulent Flow	375
§12.1	Temperature Fluctuations and the Time-Smoothed Temperature	375
*§12.2	Time-Smoothing the Energy Equation	377
*§12.3	Semiempirical Expressions for the Turbulent Energy Flux	379
	<i>*Example 12.3-1. Temperature Profiles in Steady Turbulent Flow in Smooth Circular Tubes, 380</i>	
§12.4	The Double Temperature Correlation and Its Propagation: The Corrsin Equation	384
	<i>Example 12.4-1. Decay Equation for the Double Temperature Correlation, 386</i>	
Chapter 13	Interphase Transport in Nonisothermal Systems	389
*§13.1	Definition of the Heat-Transfer Coefficient	390
	<i>*Example 13.1-1. Calculation of Heat-Transfer Coefficients from Experimental Data, 394</i>	
§13.2	Heat-Transfer Coefficients for Forced Convection in Tubes	396
	<i>*Example 13.2-1. Design of a Tubular Heater, 405</i>	
*§13.3	Heat-Transfer Coefficients for Forced Convection around Submerged Objects	407
§13.4	Heat-Transfer Coefficients for Forced Convection through Packed Beds	411
*§13.5	Heat-Transfer Coefficients for Free Convection	412
	<i>*Example 13.5-1. Heat Loss by Free Convection from a Horizontal Pipe, 414</i>	
§13.6	Heat-Transfer Coefficients for Condensation of Pure Vapors on Solid Surfaces	415
	<i>Example 13.6-1. Condensation of Steam on a Vertical Surface, 418</i>	

Chapter 14 Energy Transport by Radiation

*§14.1	The Spectrum of Electromagnetic Radiation	426
*§14.2	Absorption and Emission at Solid Surfaces	427
*§14.3	Planck's Distribution Law, Wien's Displacement Law, and the Stefan-Boltzmann Law	433
	<i>*Example 14.3-1. Temperature and Radiant-Energy Emission of the Sun, 437</i>	
*§14.4	Direct Radiation between Black Bodies in Vacuo at Different Temperatures	437
	<i>*Example 14.4-1. Estimation of the Solar Constant, 443</i>	
	<i>*Example 14.4-2. Radiant Heat Transfer between Disks, 444</i>	
*§14.5	Radiation between Nonblack Bodies at Different Temperatures	445
	<i>*Example 14.5-1. Radiation Shields, 446</i>	
	<i>*Example 14.5-2. Radiation and Free-Convection Heat Losses from a Horizontal Pipe, 448</i>	
	<i>Example 14.5-3. Combined Radiation and Convection, 448</i>	
§14.6	Radiant Energy Transport in Absorbing Media	449
	<i>Example 14.6-1. Absorption of a Monochromatic Radiant Beam, 451</i>	
Chapter 15	Macroscopic Balances for Nonisothermal Systems	456
*§15.1	The Macroscopic Energy Balance	456
*§15.2	The Macroscopic Mechanical Energy Balance (Bernoulli Equation)	460
*§15.3	Summary of the Macroscopic Balances for Pure Fluids	462
*§15.4	Use of the Macroscopic Balances for Solving Steady-State Problems	463
	<i>*Example 15.4-1. The Cooling of an Ideal Gas, 463</i>	
	<i>*Example 15.4-2. Parallel- or Counter-Flow Heat Exchangers, 465</i>	
	<i>*Example 15.4-3. Power Requirements for Pumping a Compressible Fluid through a Long Pipe, 467</i>	
	<i>Example 15.4-4. Mixing of Two Ideal-Gas Streams, 470</i>	
	<i>*Example 15.4-5. Flow of Compressible Fluids through Heat Meters, 471</i>	
§15.5	Use of the Macroscopic Balances for Solving Unsteady-State Problems	473
	<i>Example 15.5-1. Heating of a Liquid in an Agitated Tank, 473</i>	
	<i>Example 15.5-2. Operation of a Simple Temperature Controller, 476</i>	
	<i>Example 15.5-3. Free Batch Expansion of a Compressible Fluid, 480</i>	

PART III MASS TRANSPORT**Chapter 16 Diffusivity and the Mechanisms of Mass Transport 495**

- *§16.1 Definitions of Concentrations, Velocities, and Mass Fluxes
Example 16.1-1. Relations among the Molar Fluxes, 501 496
- *§16.2 Fick's Law of Diffusion 502
- *§16.3 Temperature and Pressure Dependence of Mass Diffusivity
**Example 16.3-1. Estimation of Mass Diffusivity at Low Density, 507* 504
- *Example 16.3-2. Estimation of Mass Diffusivity at High Density, 507*
- §16.4 Theory of Ordinary Diffusion in Gases at Low Density
Example 16.4-1. Computation of Mass Diffusivity at Low Density, 512 508
- §16.5 Theories of Ordinary Diffusion in Liquids
Example 16.5-1. Estimation of Mass Diffusivity for a Binary Liquid Mixture, 515 513

Chapter 17 Concentration Distributions in Solids and in Laminar Flow 519

- *§17.1 Shell Mass Balances: Boundary Conditions 521
- *§17.2 Diffusion Through a Stagnant Gas Film
**Example 17.2-1. Determination of Diffusivity, 526*
Example 17.2-2. Diffusion Through a Nonisothermal Spherical Film, 527 522
- *§17.3 Diffusion with Heterogeneous Chemical Reaction
**Example 17.3-1. Diffusion with Slow Heterogeneous Reaction, 531* 529
- §17.4 Diffusion with Homogeneous Chemical Reaction
**Example 17.4-1. Gas Absorption with Chemical Reaction in an Agitated Tank, 534* 532
- *§17.5 Diffusion into a Falling Liquid Film: Forced-Convection Mass Transfer 537
**Example 17.5-1. Gas Absorption from Rising Bubbles, 541*
- §17.6 Diffusion and Chemical Reaction Inside a Porous Catalyst: the "Effectiveness Factor" 542

Chapter 18 The Equations of Change for Multicomponent Systems 554

- *§18.1 The Equations of Continuity for a Binary Mixture 555
- *§18.2 The Equation of Continuity of A in Curvilinear Coordinates 558
- §18.3 The Multicomponent Equations of Change in Terms of the Fluxes 560

- §18.4 The Multicomponent Fluxes in Terms of the Transport Properties 563
- §18.5 Use of the Equations of Change to Set Up Diffusion Problems
Example 18.5-1. Simultaneous Heat and Mass Transfer, 572 572

- Example 18.5-2. Thermal Diffusion, 574*
- Example 18.5-3. Pressure Diffusion, 575*
- Example 18.5-4. Forced Diffusion, 577*
- Example 18.5-5. Three-Component Ordinary Diffusion with Heterogeneous Chemical Reaction, 578*
- *§18.6 Dimensional Analysis of the Equations of Change for a Binary Isothermal Fluid Mixture
**Example 18.6-1. Blending of Miscible Fluids, 582* 580

Chapter 19 Concentration Distributions with More Than One Independent Variable 592

- §19.1 Unsteady Diffusion
Example 19.1-1. Unsteady-State Evaporation, 594
Example 19.1-2. Unsteady Diffusion with First-Order Reaction, 598
Example 19.1-3. Gas Absorption with Rapid Chemical Reaction, 599 594
- §19.2 Boundary-Layer Theory: von Kármán Approximate Method
Example 19.2-1. Unsteady Evaporation into a Multicomponent Mixture, 602
Example 19.2-2. Diffusion and Chemical Reaction in Isothermal Laminar Flow Along a Soluble Flat Plate, 605 601
- §19.3 Boundary-Layer Theory: Exact Solutions for Simultaneous Heat, Mass, and Momentum Transfer
Example 19.3-1. Calculation of Mass-Transfer Rate, 619 608

Chapter 20 Concentration Distributions in Turbulent Flow 626

- *§20.1 Concentration Fluctuations and the Time-Smoothed Concentration 626
- *§20.2 Time-Smoothing of the Equation of Continuity of A 627
- §20.3 Semiempirical Expressions for the Turbulent Mass Flux
Example 20.3-1. Concentration Profiles in Turbulent Flow in Smooth Circular Tubes, 630
Example 20.3-2. Evaporation of Ammonia in a Wetted Wall Column, 630 629
- §20.4 The Double Concentration Correlation and Its Propagation: the Corrsin Equation 633

Chapter 21 Interphase Transport in Multicomponent Systems 636

- *§21.1 Definition of Binary Mass-Transfer Coefficients in One Phase 637
- *§21.2 Correlations of Binary Mass-Transfer Coefficients in One Phase at Low Mass-Transfer Rates 642
 - **Example 21.2-1. Evaporation of a Freely Falling Drop, 648*
 - **Example 21.2-2. The Wet-and-Dry-Bulb Psychrometer, 649*
- *§21.3 Definition of Binary Mass-Transfer Coefficients in Two Phases at Low Mass-Transfer Rates 652
- *§21.4 Definition of the Transfer Coefficients for High Mass-Transfer Rates 656
- §21.5 Transfer Coefficients at High Mass-Transfer Rates: Film Theory 658
 - Example 21.5-1. Rapid Evaporation of a Pure Liquid, 666*
 - Example 21.5-2. Use of Correction Factors in Droplet Evaporation, 667*
 - Example 21.5-3. Wet-Bulb Performance at High Mass-Transfer Rates, 667*
- §21.6 Transfer Coefficients at High Mass-Transfer Rates: Penetration Theory 668
- §21.7 Transfer Coefficients at High Mass-Transfer Rates: Boundary-Layer Theory 672
 - Example 21.7-1. Rapid Evaporation from a Plane Surface, 676*
- §21.8 Transfer Coefficients in Multicomponent Systems *Example 21.8-1. Mass Transfer in a Fixed-Bed Catalytic Reactor, 678* 676

Chapter 22 Macroscopic Balances for Multicomponent Systems 685

- *§22.1 The Macroscopic Mass Balances 686
- *§22.2 The Macroscopic Momentum Balance 688
- §22.3 The Macroscopic Energy Balance 689
- *§22.4 The Macroscopic Mechanical Energy Balance 689
- *§22.5 Use of the Macroscopic Balances to Solve Steady-State Problems 690
 - **Example 22.5-1. Energy Balance for a Sulfur Dioxide Converter, 690*
 - **Example 22.5-2. Height of a Packed-Tower Absorber, 692*
 - Example 22.5-3. Expansion of a Reactive Gas Mixture through a Frictionless Adiabatic Nozzle, 697*
- §22.6 Use of the Macroscopic Balances for Solving Unsteady-State Problems 700
 - Example 22.6-1. Start-Up of a Chemical Reactor, 700*
 - Example 22.6-2. Unsteady Operation of a Packed Column, 702*

Appendix A Summary of Vector and Tensor Notation 715

- §A.1 Vector Operations from a Geometrical Viewpoint 716
- §A.2 Vector Operations from an Analytical Viewpoint 719
 - Example A.2-1. Proof of a Vector Identity, 722*
- §A.3 The Vector Differential Operations 723
- §A.4 Second Order Tensors *Example A.4-1. Proof of a Tensor Identity, 731* 726
- §A.5 Integral Operations for Vectors and Tensors 731
- §A.6 Vector and Tensor Components in Curvilinear Coordinates 733
- §A.7 Differential Operations in Curvilinear Coordinates 737
 - Example A.7-1. Differential Operations in Cylindrical Coordinates, 739*

Appendix B Tables for Prediction of Transport Properties 743

- §B.1 Intermolecular Force Parameters and Critical Properties 744
- §B.2 Functions for Prediction of Transport Properties of Gases at Low Densities 746

Appendix C Constants and Conversion Factors 747

- §C.1 Mathematical Constants 747
- §C.2 Physical Constants 747
- §C.3 Conversion Factors 748

Notation 757

Author Index 765

Subject Index 769